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## Original research article

## Temporal hooking variability among sharks on south-eastern Australian demersal longlines and implications for their management

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## ABSTRACT

An experiment was done to quantify species-specific variation in temporal hooking rates from demersal longlines targeting various carcharhinids off south eastern Australia, with a view to reducing the incidental catches of protected species, including the scalloped hammerhead *Sphyrna lewini*, great hammerhead *Sphyrna mokarran* and grey nurse *Carcharias taurus*. The longline comprised a 9600 m mainline, separated into four sections (termed lines) each with 120 gangions (20 m apart) rigged with hook timers and 16/0 circle hooks baited with either sea mullet *Mugil cephalus* or eastern Australian salmon *Arripis trutta*. The mainline was deployed on each of 17 nights (between 19:30 and 23:30 h), with two lines retrieved after 7 and 14 h respectively. From a total of 8160 hooks, 246 timers were activated without hooking fish. Twenty-two species comprising 684 individuals were caught, including 52 *S. lewini*, 12 *C. taurus*, 11 *S. mokarran* and 1 loggerhead turtle *Caretta caretta*. Several environmental factors, including water temperature, moon phase and depth had mostly homogeneous, positive effects on catches. The only identified variables that might be used to considerably reduce the catches of *Sphyrna* were soak time and/or diurnal gear retrieval, with most individuals hooked during daylight. Simply mandating shorter deployments and within nocturnal retrieval might limit exploitation, especially among juveniles (<150 cm total length). For the studied fishery to approach sustainability, future research is required to investigate other gear modifications for improving size and species selectivity, and/or operational procedures for mitigating discard and escape mortalities.

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## 1. Introduction

For the past 75 years, as part of a collectively managed commercial hook-and-line fishery in New South Wales (NSW) Australia, various large sharks including sandbar *Carcharhinus plumbeus*, common black tip *C. limbatus*, tiger *Galeocerdo cuvier*, dusky *C. obscurus* and spinner *C. brevipinna* routinely have been targeted (across all sizes) using demersal longlines (Macbeth et al., 2009). As part of commercial fishing reforms, the number of fishers was restricted in 1997, after which annual shark catches (150–220 mt of eviscerated weight) remained fairly steady until 2004–2007 when effort increased for

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carcharhinids; predominantly in response to international demand for fins (Macbeth et al., 2009). By 2007, total eviscerated weights had reached ~460 mt p.a. Owing to what were considered unsustainable catches, restrictions were implemented at a total allowable combined catch of 160 mt for large shark species (i.e. carcharhinids) and a 500 kg weekly trip limit (Macbeth et al., 2009). Currently, the fishery is worth ~A\$5.6 million annually and although 337 endorsed fishers are permitted to use up to 1200 hooks per day, only ~35% reported sharks in their annual catches between 2009 and 2013 (D. Ferrell—NSW DPI, pers comm).

In addition to the harvested catches, NSW demersal longliners historically have caught and discarded various unwanted organisms (collectively termed 'bycatch') (Macbeth et al., 2009). While few quantitative studies are available, it is known that bycatches can include threatened, endangered or protected (TEP) sharks, which under NSW state government classification include the great hammerhead *Sphyrna mokarran* (classified as vulnerable), scalloped hammerhead *S. lewini* (endangered), grey nurse *Carcharias taurus* (critically endangered) and great white *Carcharodon carcharias* (vulnerable). Populations of all four species have been seriously depleted through overfishing, but of particular concern is *C. taurus*, with an estimated Australian east coast population of fewer than 1662 individuals (Lincoln Smith and Roberts, 2010). The potential for at least some associated mortalities of these four species during discarding has raised concerns over negative impacts on stocks (Macbeth et al., 2009; Robbins et al., 2013) and the subsequent cascading ecological consequences (Stevens et al., 2000; Ferretti et al., 2010; Worm et al., 2013).

The sustainability issues faced by the NSW demersal longline fishery are by no means unique, with global concerns directed towards many elasmobranch fisheries (Barker and Schluessel, 2005; Walker, 2007; Worm et al., 2013). The key issues reflect the slow growth and time to reach maturity, followed by low fecundity and long reproductive cycles of many species (Stevens et al., 2000). Such life history strategies mean that although some shark fisheries can be sustainably managed, in many cases there is a high danger of over exploitation, especially among larger species (Walker, 1998; Ferretti et al., 2008).

Like all aquatic resources, pivotal to sustainably managing shark populations is species-specific information on their biology, habitats and ecology, and the factors affecting their selection among fishing gears (Barker and Schluessel, 2005; Walker, 2007). The latter is particularly important, because it can facilitate appropriate targeting, and minimise key components of unaccounted fishing mortality (Broadhurst et al., 2006).

Unaccounted fishing mortality has been separated into various subcomponents, although of greatest concern for passive gears such as longlines are mortalities associated with discarding (on board the vessel) and escaping or dropping off hooks. Seldom are these latter mortalities quantified, let alone included in total allowable catch calculations. Irrespective of the fishing gear, there are three broad applied strategies for minimising unaccounted fishing mortality, including: (1) spatial and temporal effort regulation—either within (Ward et al., 2008; Beverly et al., 2009) or among gears (Hazin et al., 2008); (2) gear modifications to improve species and size selection (Erickson et al., 2000; Ford et al., 2008); and (3) modified handling practices that minimise discard mortality (Gilman et al., 2005; Milliken et al., 2009).

All three strategies have different utilities depending on the fishery and gear configurations being assessed. Further, one or more methods can be used in isolation or consecutively (Broadhurst et al., 2006). For longlines, where fishing success strongly relies on appropriate deployment within the required spatial and temporal scales (Medved et al., 1985; Stoner and Kaimmer, 2008), quantifying species-specific factors affecting catches might help to minimise unwanted mortalities. This would be considered a coherent starting point for any shark fishery that seeks to alleviate collateral impacts, and perhaps might ideally precede technical gear modifications—especially with the recent advancements in vessel monitoring systems (i.e. to facilitate compliance). In some cases, regulating and enforcing spatial and temporal deployments might be considered a viable option for improving selectivity.

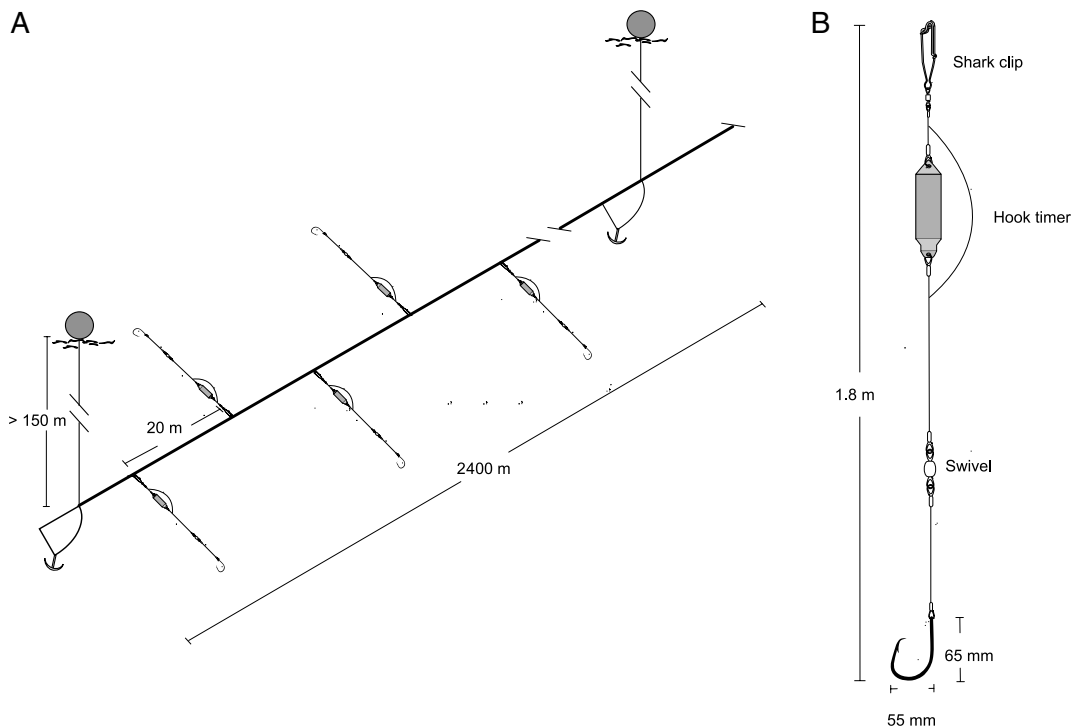
Given the logic above, and considering there are limited relevant scientific data, the main aim of this study was to explore the potential for differences in temporal hooking among key target and non-target species, and any explanatory factors for the NSW demersal longline fishery. A secondary aim was to use this information to suggest coherent mechanisms by which effort might be regulated to improve selectivity (i.e. within strategy 1 above).

## 2. Methods

The research was completed on board two longliners (14 and 19 m, respectively) deploying the same conventional fishing gear off northern New South Wales (NSW), Australia during 17 fishing trips in 2013 (23 and 24 January; 7–9 February; 7, 9, 10, 14, 29 and 30 April; 8, 12, 14 and 15 May; and 5 and 6 June). All sampling was opportunistically done within the conventional spatial (between Nambucca Heads–30°34'S153°13'E and Wooli–29°56'S153°26'E) and temporal (January to July) ranges of the northern NSW demersal longline fishery (described by Macbeth et al., 2009).

### 2.1. Fishing gear and sampling

The longline comprised a 9600 m, 3.2 mm diameter (Ø) monofilament polyamide (PA) mainline, separated into four 2400 m sections (termed 'lines') by weights (30 kg), and ropes (8 mm Ø, polypropylene) leading to floats (30 mm Ø; Fig. 1A). Each of the four lines had 120 gangions (attached 20 m apart), comprising a stainless-steel clip rigged with 3.6 m of 3.2 mm Ø monofilament PA separated with a 70 mm, 60 g swivel, and terminating in a 16/0 stainless-steel, non-offset circle hook



**Fig. 1.** Schematic representation of (A) one of the four deployed lines and (B) expanded view of a gangion with hook timer attached.

(Fig. 1B). All hooks were baited either with 0.3 kg of sea mullet *Mugil cephalus* or eastern Australian salmon *Arripis trutta*. The gangions were also fitted with hook timers (HT 600, Lindgren-Pitman Inc.—following Sigler, 2000), which were activated when >4.53 kg of pressure was exerted on the hooks (Fig. 1B). To maintain bottom contact, weights (6–8 kg) were secured to the lines between every 10 gangions. Eight water temperature loggers (Vemco Ltd, Nova Scotia, Canada) were also attached to the mainline and one to the surface floats at each end of the longline.

On each of 17 fishing days, the longline was deployed between 19:30 and 23:30 h on the seabed in depths of 50–100 m (~3–10 nm off shore). Two lines (240 hooks) were retrieved after a minimum of 7 h and the other two lines (remaining 240 hooks) after 14 h. During retrieval, each hook timer was noted (line and hook number) and assessed as it came on board (irrespective of whether an animal was hooked) and the time recorded. Any hooks that were missing or timers that were activated but had no hooked catch were also noted. All hooked catches were either brought on board (retained) or alongside the vessel (e.g. those that were protected or unwanted), where they were assessed to confirm species identification and, if possible, their total length (TL) in the natural position (following Compagno, 1984) or for sea turtles their curved carapace length (CCL) to the nearest cm. Additionally, sex and maturation status (i.e. immature or mature based on TL, or following previous definitions for other elasmobranchs; e.g. Macbeth et al., 2009) were obtained prior to release or processing. To minimise impacts, some individuals (e.g. *C. taurus*) were immediately released without obtaining all of the above data. Other daily technical and environmental data collected included the date, times of hook deployment (setting) and retrieval (to provide ‘soak time’), location, bottom depth, swell and sea conditions, current and direction, wind speed and direction, moon rise and set, sun rise and set, moon phase and percentage visible, surface and bottom water temperatures, and the presence or absence of rain.

## 2.2. Statistical analyses

For species or genera where there were sufficient data (defined as >20 individuals), the various fixed continuous and categorical biological, technical and environmental effects, and any coherent interactions were all considered along with appropriate random terms (e.g. ‘lines’ and ‘days’) in separate mixed-effects models fitted to test the hypothesis of no interspecific/generic differences (termed ‘taxonomic group’) among the (1) numbers caught (per line), and (2) elapsed time until hooking (obtained from the individual hook timers). For each analysis, a forward variable selection algorithm was employed with a  $p$ -value of  $\leq 0.05$  required for a variable to be added to the model. Significant terms for categorical variables were centred for confounding effects and subsequently explored using the Benjamini–Hochberg–Yekutieli procedure to control the false discovery rate (FDR; Benjamini and Yekutieli, 2001). Fits to the numbers caught were obtained using the generalised linear mixed model (GLMM) function `glmer` in the `lme4` package of the freely available R language, while fits to the elapsed times used linear mixed models (LMM) were obtained using the `lmer` function.

**Table 1**

Scientific and common names, numbers, and where collected, percentage sexually immature (PSI), sex ratios (female:male) and sizes (including the range and mean  $\pm$  SD total length) of organisms caught during the experiment. –, not collected. Not all individuals of all species were able to be assessed for sex or maturation.

Family	Scientific name	Common name	No	PSI	Sex ratio	Sizes
<i>Elasmobranchs</i>						
Carcharhinidae	<i>Galeocerdo cuvier</i>	Tiger shark	123	98.1	1:0.73	100–426; 185 $\pm$ 50
	<i>Carcharhinus plumbeus</i>	Sandbar shark	160	18.1	1:0.89	97–232; 191 $\pm$ 27
	<i>C. limbatus</i>	Common black tip shark	113	61.7	1:6.47	95–300; 197 $\pm$ 31
	<i>C. obscurus</i>	Dusky shark	74	19.4	1:1.09	100–410; 310 $\pm$ 71
	<i>C. brevipinna</i>	Spinner shark	50	56.3	1:1.05	100–307; 206 $\pm$ 59
	<i>C. brachyurus</i>	Bronze shark	6	0	1:3	230–290; 259 $\pm$ 42
	<i>C. leucas</i>	Bull shark	1	0	0:1	311
	<i>Dasyatis brevicaudata</i>	Smooth stingray	18	–	–	100–250; 173 $\pm$ 55
Dasyatidae	<i>Carcharias taurus</i>	Grey nurse shark	12	–	–	180–306; 236 $\pm$ 51
Odontaspidae	<i>Orectolobus maculatus</i>	Spotted wobbegong	10	50.0	1:1	96–159; 122 $\pm$ 22
	<i>O. ornatus</i>	Ornate wobbegong	5	100	0:1	90–130; 108 $\pm$ 18
	<i>O. halei</i>	Banded wobbegong	3	33.3	1:3	83–184; 134 $\pm$ 51
Rhynchobatidae	<i>Rhynchobatus australiae</i>	White-spotted guitarfish	8	–	3:1	171–226; 203 $\pm$ 20
Rhinobatidae	<i>Aptychotrema rostrata</i>	Eastern shovelnose ray	2	–	–	70–80; 75 $\pm$ 7
Sphyrnidae	<i>Sphyrna lewini</i>	Scalloped hammerhead	52	94.2	1:1.08	130–257; 182 $\pm$ 31
	<i>S. zygaena</i>	Smooth hammerhead	2	100	0:1	160–186; 173 $\pm$ 18
	<i>S. mokarran</i>	Great hammerhead	11	9.1	1:2.33	241–338; 302 $\pm$ 30
Triakidae	<i>Mustelus antarcticus</i>	Gummy shark	22	90.5	9.5:1	64–114; 98 $\pm$ 12
<i>Teleosts</i>						
Ariidae	<i>Neoarius graeffei</i>	Blue catfish	3	–	–	–
Rachycentridae	<i>Rachycentron canadum</i>	Cobia	7	–	–	79–114; 97 $\pm$ 13
Sparidae	<i>Pagrus auratus</i>	Pink snapper	1	–	–	83
<i>Reptiles</i>						
Cheloniidae	<i>Caretta caretta</i>	Loggerhead turtle	1	–	–	100

### 3. Results

During the 17 daily deployments (total of 8160 hooks set across a mean depth  $\pm$  SD of 67.82  $\pm$  10.71 m), 246 timers were activated without anything being hooked and retained, including 65 hooks that were missing within 0.3 m above the hook. Twenty-two species comprising 684 individuals were caught (including 42 animals on hooks that were inadvertently deployed without timers), and either brought on board and retained, or released alongside the vessel (Table 1). A total of 76 individuals of TEP species were caught, including 52 *Sphyrna lewini* and 12 *Carcharias taurus*. For those species that were assessed, large percentages of their catches were immature (Table 1).

In terms of catch-per-unit-effort (CPUE), the overall total was 8.38 individuals per 100 hooks. The dominant retained species were *Carcharhinus plumbeus* (23%; 1.96 per 100 hooks), *Galeocerdo cuvier* (18%; 1.51 per 100 hooks), *Carcharhinus limbatus* (17%; 1.38 per 100 hooks) and *Carcharhinus obscurus* (11%; 0.91 per 100 hooks); most of which had sex ratios biased slightly towards males and encompassed both immature and mature individuals (Table 1). Of the hooked individuals, 72 failed to activate the timers, and were mostly small sharks (<150 mm TL), including nearly all gummy sharks *Mustelus antarcticus* (mostly gravid females) and wobbegongs *Orectolobus* spp.

To provide sufficient data for analyses, four species and genera groupings were chosen: (1) *Galeocerdo cuvier*, (2) *Mustelus antarcticus*, (3) *Carcharhinus* (six species), and (4) *Sphyrna* (three species) (Table 1). The selected GLMM describing the numbers caught per line included the fixed main effects of taxonomic group (the four levels above) and water depth, and first order interactions between taxonomic group and soak time, water temperature, and setting time; all of which were significant ( $p < 0.05$ ; Table 2, Figs. 2 and 3). For the main effects, the differences in catches among taxonomic groups followed the absolute numbers in Table 1. Irrespective of species, and reflecting spatial effort, >50% of sharks were hooked from bottom depths of between 70 and 80 m (LMM,  $p < 0.05$ ; Table 2, Fig. 2).

False-discovery-rate pair-wise comparisons successfully separated the three interactions, with the majority of *Sphyrna* caught after significantly longer soak times (and typically during day light) than all other species, while *Carcharhinus* and *Galeocerdo cuvier* were similarly caught across significantly longer soak times than *Mustelus antarcticus* ( $p < 0.05$ ; Table 2, Fig. 3A). Many *M. antarcticus* also were caught during cooler water (between 18 and 20 °C) than the remaining species, all of which were mostly hooked when bottom temperatures were >20 °C (FDR,  $p < 0.05$ ; Table 2, Fig. 3B). *Mustelus antarcticus* were also more readily hooked across significantly earlier setting times of the longline than *Carcharhinus* and *Galeocerdo cuvier* (FDR,  $p < 0.05$ ; Table 2, Fig. 3C).

The selected LMM explaining variability among the elapsed time until hooking comprised the significant fixed main effects of taxonomic group, setting time and moon phase, and first order interactions between taxonomic group and their TL and bottom depth ( $p < 0.05$ ; Table 2, Figs. 4–6). *Mustelus antarcticus* were not included in this analysis, because very few activated the hook timers. *Sphyrna* were hooked after significantly longer soak times than *Carcharhinus* (FDR,  $p < 0.05$ ), but there were no significant differences between *Galeocerdo cuvier* and the other taxonomic groups (FDR,  $p > 0.05$ ; Table 2, Fig. 4). Irrespective of the three taxonomic groups, the overall elapsed time until hooking had negative relationships with

**Table 2**

Summary of main fixed effects and interactions and their significance in selected mixed models on (1) numbers caught per line, and (2) elapsed time until hooking for *Carcharhinus*, *Sphyrna*, *Mustelus antarcticus* and *Galeocerdo cuvier* (taxonomic group) and where relevant, false discovery rate (FDR) pairwise comparisons.

Fixed effects	P	Significant FDR comparisons ( $p < 0.05$ )
(1) Numbers of catches		
Taxonomic group	**	Among all comparisons
Depth	*	
Taxonomic group $\times$ soak time	*	Among all, except for <i>Carcharhinus</i> vs <i>G. cuvier</i>
Taxonomic group $\times$ temperature	*	<i>M. antarcticus</i> vs all other groups
Taxonomic group $\times$ setting time	*	<i>Carcharhinus</i> vs <i>M. antarcticus</i> ; <i>G. cuvier</i> vs <i>M. antarcticus</i>
(2) Elapsed time until hooking		
Taxonomic group	**	<i>Carcharhinus</i> vs <i>Sphyrna</i>
Setting time	*	NA
>50% moon	*	NA
Taxonomic group $\times$ total length	*	<i>Sphyrna</i> vs <i>Carcharhinus</i> ; <i>Sphyrna</i> vs <i>G. cuvier</i>
Taxonomic group $\times$ depth	*	None detected

NA-not applicable

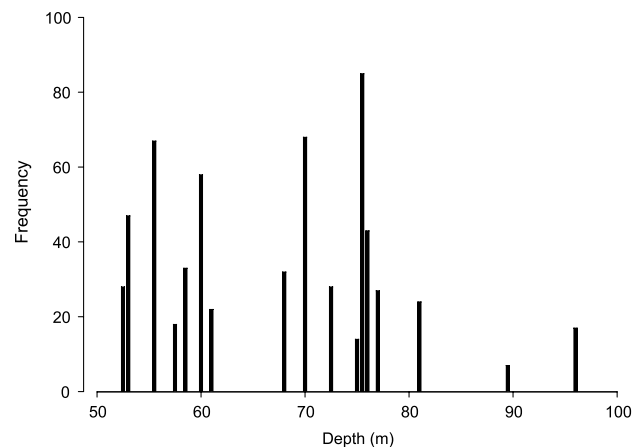
\*  $p < 0.05$ .

\*\*  $p < 0.01$ .

**Table 3**

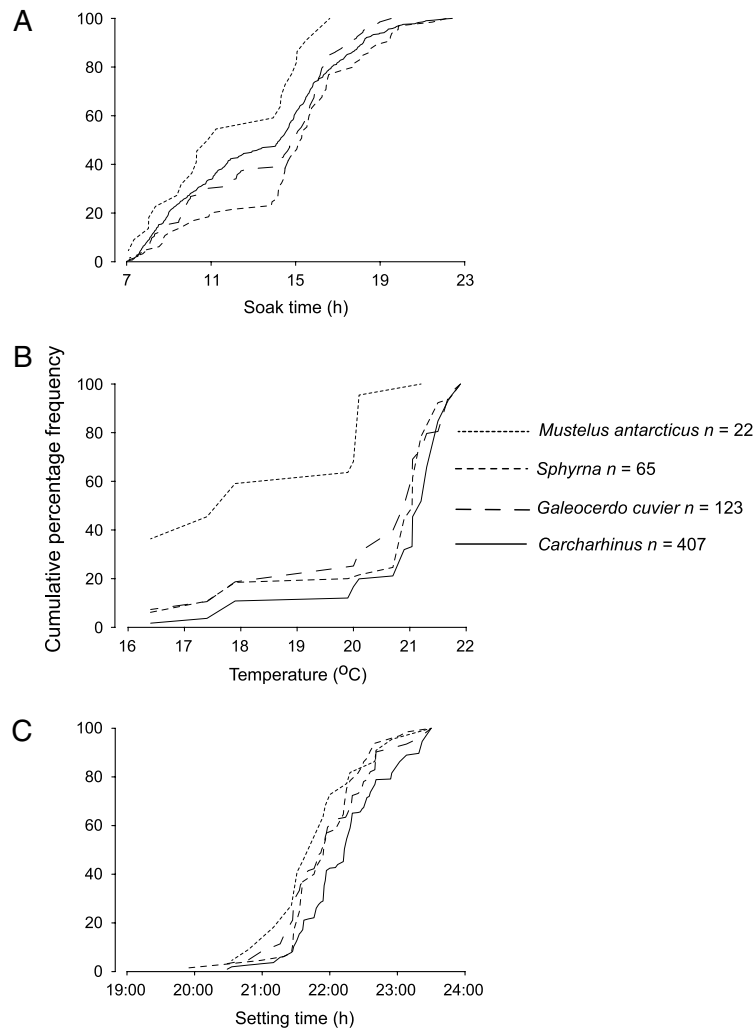
Summary of key environmental and technical factors (means ( $\pm$  SD), where relevant) describing the capture of 12 *Carcharias taurus* (mean size  $\pm$  SD of  $236 \pm 51$  cm total length) and 1 *Caretta caretta* ( $\sim 100$  cm CCL).

Variable	<i>Carcharias taurus</i>	<i>Caretta caretta</i>
Soak time (h:min)	14:26 (3:55)	11:38
Setting time (h:min)	21:48 (0:41)	22:14
Bottom temperature ( $^{\circ}$ C)	19.00 (2.12)	21.90
Elapsed time until hooking (h:min)	5:53 (3:50)	Not available
Depth (m)	69.33 (11.51)	Not available
Moon phase (% full)	46.21 (41.71)	15

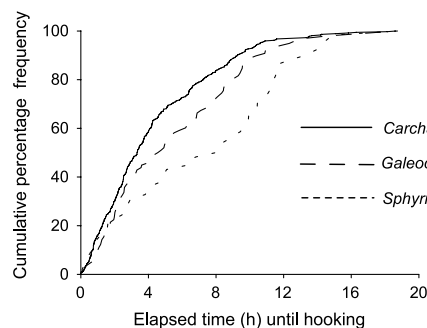
**Fig. 2.** Absolute frequencies of analysed catches (key species) plotted against capture depth.

both setting time and full-moon phase ( $3:48 \pm 0.11$  vs  $4:55 \pm 0.16$  h during  $>50$  and  $<50\%$  moon) (LMM,  $p < 0.05$ ; Table 2, Fig. 5). False-discovery-rate pairwise comparisons of the significant interaction between taxonomic group and TL revealed that there was a stronger negative relationship between TL and the elapsed time of hooking for *Sphyrna* than for *Carcharhinus* and especially *G. cuvier* ( $p < 0.05$ ; Table 2, Fig. 6A, C and E). Despite the significant interaction between taxonomic group and bottom depth, FDRs failed to separate the treatments ( $p > 0.05$ ; Table 2, Fig. 6B, D and F).

While insufficient numbers of the two other protected species (*Carcharias taurus* and loggerhead turtle *Caretta caretta*) were caught to enable analyses, their key details are included in Table 3. Four of the 12 *C. taurus* were caught on the same line and three of them within 120 m of each other during the first day (January) and another two together on the fifth day within 60 m of each other, with the rest distributed among the remaining days. Most were caught during the night or close to dawn. The single *C. caretta* was hooked in the flipper (without activating the timer) and still quite active.



**Fig. 3.** Cumulative percentage frequencies of *Mustelus antarcticus*, *Sphyrna*, *Galeocerdo cuvier* and *Carcharhinus* caught plotted against (A) mainline soak time, (B) bottom temperature and (C) mainline setting time.

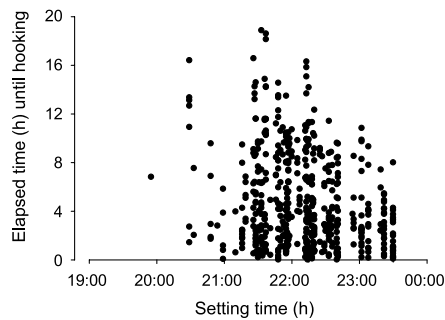


**Fig. 4.** Relationship between the elapsed time until hooking and the cumulative percentage frequencies of *Carcharhinus*, *Galeocerdo cuvier* and *Sphyrna*.

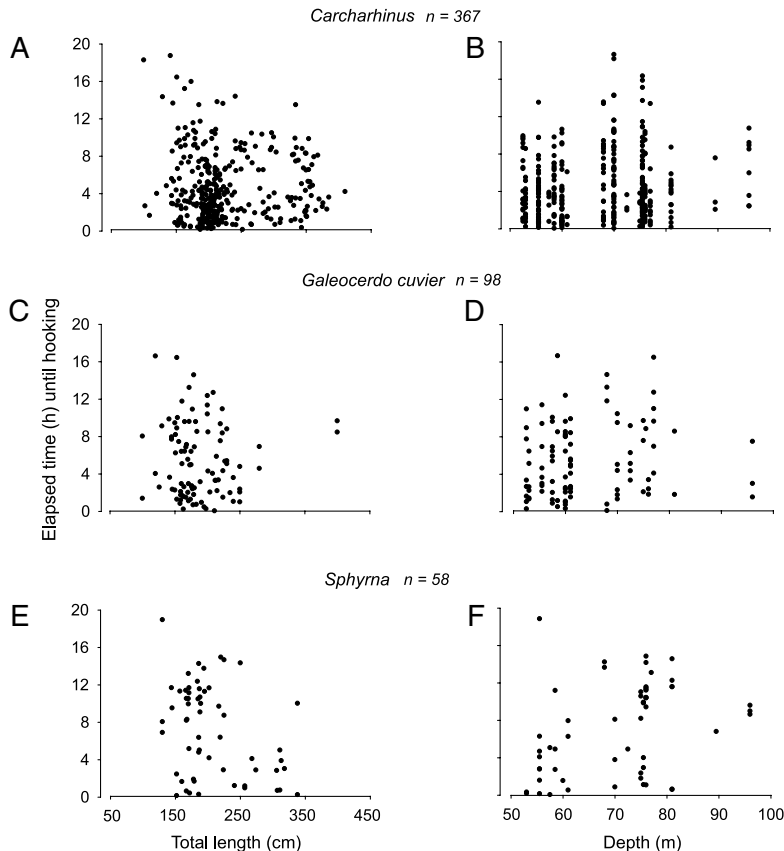
#### 4. Discussion

The catch composition observed in this study was comparable to the known landed harvests, and the earlier observer-based work by Macbeth et al. (2009). Similarly, the CPUE of the targeted *Carcharhinus plumbeus* (1.96 sharks per 100 hooks) only slightly exceeded that (1.48 sharks per 100 hooks) observed by Macbeth et al. (2009). However, most other species were caught here at considerably greater CPUEs, which may reflect the considerable reduction in fishing effort over recent





**Fig. 5.** Relationship between the setting time and elapsed time until hooking for pooled catches of *Carcharhinus*, *Galeocerdo cuvier* and *Sphyrna*.



**Fig. 6.** Relationships between the elapsed time until hooking and the total length (cm) and depth of capture (m) of (A and B) *Carcharhinus*, (C and D) *Galeocerdo cuvier*, and (E and F) *Sphyrna*.

years. Notwithstanding this somewhat positive result, the sizes of sharks remained comparable between studies, and for most species large proportions were immature, especially for *Galeocerdo cuvier*, *C. limbatus*, *C. brevippina* and *Sphyrna lewini*; nearly all of which were caught across mean sizes comparable to, or smaller than, those at maturity (Camhi et al., 1998; Joung et al., 2005; Last and Stevens, 2009; Geraghty et al., 2013). In particular, all but three of the 52 *S. lewini* were immature.

The large proportions of protected species (~11% of the total catch) and immature individuals of the targeted species (~53% of catches) hooked in this study strongly support introducing management procedures to improve both species and size selectivity. Although there are few data, the potential for achieving such an outcome can be discussed by considering the species-specific hooking patterns with respect to the observed biological, technical and environmental factors, and attempting to explain the key underlying mechanisms. Specifically, while there was some potential for confounding in terms of soak time and nocturnal effects, the data indicate that at least for *Sphyrna* (largely driven by *S. lewini*), regulating the short-term temporal deployment of the longline could be one option for substantially mitigating catches. In particular, 50% of *Sphyrna* were caught after sunrise, while proportionally more *Carcharhinus* (>85%) and *Galeocerdo cuvier* (>72%) were caught before sunrise; an observation that supports nocturnal gear deployment and retrieval. Further, the observed

negative relationship between TL and the elapsed time until hooking for *Sphyrna* means that shorter, nocturnal deployments might also reduce the catches of juveniles.

There are at least two possible concomitant impacts of shorter soak times. First, although discard mortality was not a focus of the present study, intuitively, restricting soak time might have positive consequences, simply because all animals would remain on the hooks for less time (Morgan and Carlson, 2010). Second, several previous studies have demonstrated a negative relationship between discard mortality and size (Broadhurst et al., 2006; Morgan and Carlson, 2010), and so for *Sphyrna* any hooking bias towards larger individuals (more capable of handling the associated impacts) might similarly reduce overall discard mortality. Although no seabird interactions were recorded in this study, nor by Macbeth et al. (2009), a third potential benefit is a lower probability of seabird predation on nocturnally retrieved baits (as a consequence of reduced visibility; Gilman et al., 2005).

In addition to the species-specific temporal influences on catches described above, there were other key parameters. For example, depth had a homogeneous effect among the key species and groups, although this might largely be attributed to the limited variability (i.e. most deployments were between 60 and 80 m). For most of the taxonomic groups, temperature had a similar effect, although the exploitation of *Mustelus antarcticus* (at least for gravid females) might be controlled by temporally regulating effort to warmer bottom temperatures ( $>20^{\circ}\text{C}$ ) when their catches were relatively fewer, but all other groups were greater. Such a result can be explained by species-specific water temperature preferences (Morgan and Carlson, 2010; Musyl et al., 2011).

Notwithstanding the above, a positive correlation between temperature and catches for most of the key species is potentially an issue, because the mortality of many discards has been shown to be similarly correlated (Broadhurst et al., 2006). Increasing temperatures evoke a range of physiological disturbances at the cellular and whole animal levels, including a greater metabolic rate and demand for oxygen; the saturation of which paradoxically decreases (Pörtner, 2002). While few studies are available, escape mortality might also be affected by water temperature (Braccini et al., 2012) and could be an issue given that over a quarter (i.e. 246 activated timers) of catches managed to escape, and presumably after incurring at least some damage. While there is no means for confirmation, such a result might at least partially explain the large proportion of *Carcharias taurus* frequently observed with hooking-related injuries (Lincoln Smith and Roberts, 2010; Robbins et al., 2013).

In terms of other parameters, bait had no effect on catches, but only two types of fish were used and this factor was confounded with other variables, such as bottom temperature. Previous studies have shown that bait type can affect the capture of various species on longlines (Broadhurst and Hazin, 2001), including elasmobranchs (Gilman et al., 2008; Godin et al., 2012). In particular, for some sharks, catches typically are greater on squid baits, possibly in response to improved bait longevity (Godin et al., 2012). Similarly, Yokota et al. (2009) identified that sea turtle catches could be limited by avoiding squid baits. Although there are few data, perhaps using fish as bait in this study limited turtle capture to one individual, which in any case might have been accidental (during retrieval). The potential for at least some species-specific effects of baits on selectivity warrants additional research.

Other bait-related options for controlling species selection might include assessing retrofitted permanent magnets and/or electropositive metals, although the utility of such modifications remains highly species-specific (Hutchinson et al., 2012). For example, although captive studies have implied the potential for success among elasmobranchs (based stimulating a sensory system specific to cartilaginous fishes; Stoner and Kaimmer, 2008; Rigg et al., 2009), a recent metadata analysis indicated that such modifications have failed to significantly reduce bycatch (Favaro and Côté, 2013). This finding may be due to substantial differences in shark behaviour between captive and wild situations. In support of this statement, Robbins et al. (2011) found that social interactions between sharks may outweigh individual responses to electro-magnetic bycatch reduction devices (BRDs), but that species that occur in lower densities or have less vigorous conspecific interactions may prove to be responsive. Nevertheless, similar BRDs should be field tested for their potential to reduce catches of *Sphyrna*, because these species have the greatest total electroreceptor pore count for any elasmobranch studied to date (Kajiura et al., 2010); implying that they may be more sensitive to negative reaction via electro-magnetic BRDs.

The bycatch of 52 *Sphyrna lewini*, 11 *S. mokarran*, 12 *Carcharias taurus* and numerous immature carcharhinids (nearly all of which are listed as threatened or vulnerable by the International Union for the Conservation of Nature) is somewhat concerning and might be sufficient to warrant fairly rapid management changes to this fishery to mitigate any associated unaccounted fishing mortality. Based on the data here, temporally restricting the deployment and retrieval of hooks to the night is an option for *Sphyrna*, but is unlikely to work for *C. taurus*. The latter species does show a preference for defined aggregation sites, which are spatially managed in NSW as 'critical habitats' (discussed by Robbins et al., 2013), but it would not be possible to completely preclude their capture through broader spatial closures to fishing.

Additional data are required to determine if the unaccounted fishing mortality of the four TEP species and the other unwanted catches can be regulated by fine-scale temporal or spatial closures and/or gear modifications. In terms of the latter, and beyond the options discussed above, simply comparing hook types and/or sizes for their size selectivity and rates of injury and mortality would be a coherent area for future research (e.g. Godin et al., 2012; Hannan et al., 2013). Similarly, on-board handling methods might be assessed for their utility in limiting the injury and mortality to some discards (Broadhurst et al., 2006). Through adequate consideration of individual species-specific responses, such data could facilitate a structured approach towards mitigating not only the capture, but more importantly the unaccounted fishing mortality of non-target catches in the NSW demersal longline fishery.



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